

Nonlinear dynamic model for magnetically-tunable Galfenol vibration absorbers

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ABSTRACT

This paper presents a single degree of freedom model for the nonlinear vibration of a metal-matrix composite manufactured by ultrasonic additive manufacturing that contains seamlessly embedded magnetostrictive Galfenol alloys (FeGa). The model is valid under arbitrary stress and magnetic field. Changes in the composite's natural frequency are quantified to assess its performance as a semi-active vibration absorber. The effects of Galfenol volume fraction and location within the composite on natural frequency are quantified. The bandwidth over which the composite's natural frequency can be tuned with a bias magnetic field is studied for varying displacement excitation amplitudes. The natural frequency is tunable for all excitation amplitudes considered, but the maximum tunability occurs below an excitation amplitude threshold of 1×10^{-6} m for the composite geometry considered. Natural frequency shifts between 6% and 50% are found as the Galfenol volume fraction varies from 25% to 100% when Galfenol is located at the composite neutral axis. At a modest 25% Galfenol by volume, the model shows that up to 15% shifts in composite resonance are possible through magnetic bias field modulation if Galfenol is embedded away from the composite midplane. As the Galfenol volume fraction and distance between Galfenol and composite midplane are increased, linear and quadratic increases in tunability result, respectively.

Keywords: vibration absorber, Galfenol, ultrasonic additive manufacturing, active composites, nonlinear vibration, nonlinear dynamic modeling

1. INTRODUCTION

The problem of vibration reduction and control has many solution strategies. Typically, these strategies are categorized by their mode of action: passive, semi-active, or active. Passive systems have no adaptability and are tuned to a specified operating condition *a priori*. Semi-active systems behave like passive systems, but have the ability to adjust their dynamic properties to counteract changes in operating conditions or dynamic properties of the structure to be controlled. Active systems *generate* dynamic stresses in the structure to destructively interfere with the dynamic stresses that cause the undesired vibration.

Smart materials are commonly used to realize semi-active and active vibration control systems. However, few smart materials can withstand tensile and shear loading or operate in harsh mechanical environments. One such material is Galfenol, a magnetostrictive alloy of iron and gallium. Galfenol's structural-grade tensile strength (~ 500 MPa),¹ ability to withstand torsion and impact, bandwidth on the order of 10 kHz, ability to be magnetized easily, and very low hysteresis are beneficial for vibration reduction systems, particularly active systems. This combination of robustness, high bandwidth, and very low hysteresis is not found in any other smart material. However, Galfenol has a relatively low actuation strain (~ 350 ppm)¹ and energy density (~ 3 kJ/m³).² This limited work output hinders active vibration control implementations. As such, semi-active vibration reduction is considered.

Galfenol's suitability for semi-active control derives from the Delta E (ΔE) effect, which is described in Figure 1. The magnetostriction present in this alloy is a measure of the strain that results from rotation of magnetic domains in the material. When Galfenol is stressed from a demagnetized state (shown by path A in Figure 1), both purely mechanical and magnetoelastic strain occur until the material becomes magnetically

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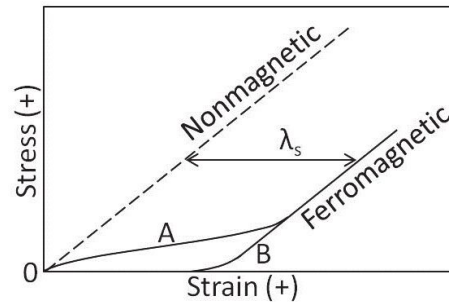


Figure 1. Stress vs strain for (A) initially demagnetized and (B) initially partially magnetized ferromagnetic materials with positive maximum magnetostriction λ_s .

saturated, after which only purely mechanical strain occurs. Thus, Galfenol's effective elastic modulus varies while its magnetic state changes.

Due to Galfenol's structural strength, it can be located directly in the load path. There are a number of techniques available for incorporating smart materials, including Galfenol, into composite structures. One powerful technique for seamlessly embedding smart materials into metal matrices is ultrasonic additive manufacturing (UAM), also known as ultrasonic consolidation. UAM is a new rapid prototyping process that works on the principle of creating solid-state, metallurgical welding at the interface between a thin metallic tape and a metallic substrate. This is accomplished by applying a static, normal compressive force between a cylindrical welding horn and the tape-substrate pair while vibrating the horn laterally at ultrasonic frequencies, as shown in Figure 2. Metallic tapes are welded side-by-side and on top of each other in an additive manner to form a bulk geometry, which may include intricate internal cavities created through periodic machining. Like all solid-state welding processes, metallurgical welding occurs below the melting temperatures of the respective metals—roughly 35% of the melting temperature for UAM.³ UAM therefore provides the unique ability to either weld or encapsulate smart materials, electronics, and fiber optics inside a metal matrix. An aluminum composite containing an embedded sheet of Galfenol that was manufactured by UAM is shown, along with a schematic of its cross section, in Figure 3.

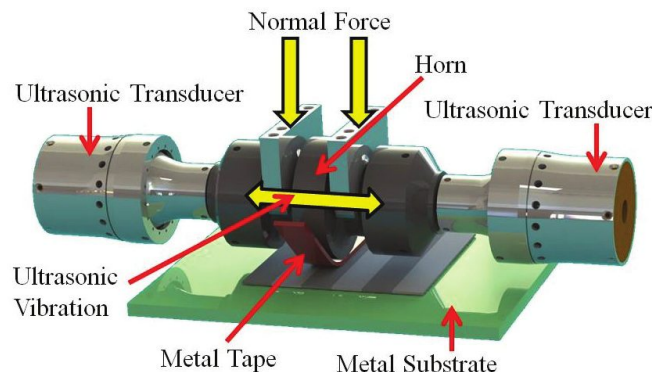


Figure 2. Schematic of the UAM process.

In this analytical study, the Al-Galfenol unimorph shown in Figure 3 with cantilever boundary conditions is considered. The unimorph beam provides the means to achieve semi-active vibration absorption via the ΔE effect, though our approach can be directly generalized to other actuator configurations. Vibration absorbers work by coupling an additional mass to the vibrating structure through a compliant member.⁴ Vibrations in the original structure are attenuated at the natural frequencies of the absorber. Tuning the absorber's natural

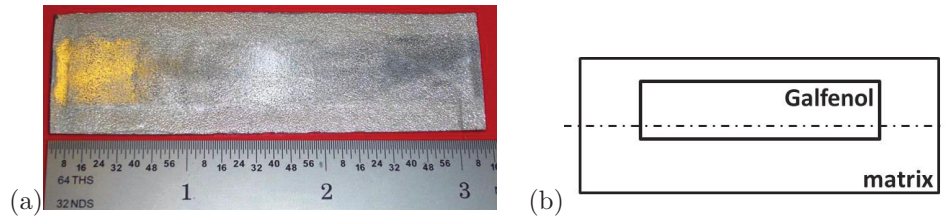


Figure 3. (a) Al-FeGa composite manufactured by UAM, and (b) cross-sectional geometry.

frequency to the disturbance frequency splits the resonance into two side bands, leaving an antiresonance at the disturbance frequency. In this paper, the Al-Galfenol composite itself acts as the compliant member with the additional advantages of electrical frequency tunability through the ΔE effect of Galfenol and compact, contactless operation enabled by the UAM embedding process. A nonlinear model is formulated to quantify the vibrations of the composite under arbitrary magnetic field and stress conditions. The effect of Galfenol volume fraction and location within the composite on the dynamic response of the composite are investigated.

2. MODEL DEVELOPMENT

Shu *et al*⁵ developed a 1D bending model of a Galfenol cantilevered unimorph by coupling Euler-Bernoulli beam theory with a linear Galfenol constitutive model. Due to the nonlinearities of magnetostrictive materials, namely magnetic saturation, hysteresis, magnetic anisotropy, and a nearly quadratic magnetostriction, linear models are accurate only for small amplitude operation about a bias point. In this research, a more general approach is considered to describe the full-scale Galfenol behavior.

A natural extension of the work by Shu *et al* would be to couple Euler-Bernoulli beam theory with a nonlinear Galfenol model. This approach is not taken due to computational considerations. The objective of the proposed model is to describe the resonance tunability of the composite through control of the bias magnetic field. Thus, the frequency domain response of the vibration is desired. Solutions exist to the nonlinear eigenvalue problem,

$$A(\lambda)v = 0, \quad (1)$$

where the dependence on λ is nonlinear, corresponding to mass, stiffness, or damping matrices that are dependent on frequency. However, magnetostrictive materials have a stiffness that is dependent on both frequency and the time-varying magnetomechanical state. Eigenvalue problems cannot be formulated for such a system. Consequently, the frequency response of composite vibration must be obtained from the time domain response by extracting the steady state vibration at a large number of discrete frequencies. As will be discussed later, both forward and reverse frequency sweeps are required, doubling the number of time domain responses that must be calculated for each frequency response. To determine the tunability of the composite's resonance, frequency responses must be calculated for a range of operating conditions. Further, it is desired to use the composite model to design effective composite geometries for resonance tuning. Therefore, nearly 10^4 time domain responses must be calculated for such a parametric study. Consequently, a simplification of the Euler-Bernoulli beam theory is employed to reduce the computational expense while retaining the full nonlinear description of the Galfenol behavior. A further reduction in computation is achieved by approximating the beam as a single degree of freedom system with an equivalent spring constant for beam bending, as shown in Figure 4.

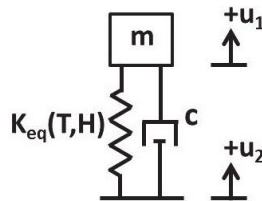


Figure 4. Idealized single degree of freedom cantilevered composite vibration system with base excitation.

2.1 Galfenol Constitutive Model

The current state of the art in practical modeling of cubic magnetostrictive materials is an efficient, fully coupled, hysteretic, three dimensional model developed by Evans and Dapino,⁶ which calculates Galfenol's magnetization and strain as functions of magnetic field and stress. This model will be referred to as the discrete energy-averaged model (DEAM). The anhysteretic, one-dimensional formulation of this model is utilized for computational efficiency. In the DEAM, energy expressions describe the rotation of magnetic moments resulting from the application of stress $\mathbf{T} = (T_1, T_2, T_3, T_4, T_5, T_6)^T$ and magnetic field $\mathbf{H} = (H_1, H_2, H_3)^T$. Table 1 summarizes the energy terms for the k^{th} magnetic domain orientation,^{6,7} where \mathbf{c}^k are the magnetically easy crystal directions at zero stress and magnetic field, K^k and K_0^k are anisotropy constants, M_s is the saturation magnetization, and μ_0 is the magnetic permeability of free space.

Table 1. Energies of the magnetic domain orientations in the DEAM.⁷

Anisotropy	Magnetomechanical coupling	Zeeman (Magnetic Field)
$\frac{1}{2}K^k \mathbf{m}^k - \mathbf{c}^k ^2 + K_0^k$	$-\mathbf{S}_m^k \cdot \mathbf{T}$	$-\mu_0 M_s \mathbf{m}^k \cdot \mathbf{H}$

The total free energy G^k is represented in matrix form as,

$$G^k = \frac{1}{2} \mathbf{m}^k \cdot \mathbf{K}^k \mathbf{m}^k - \mathbf{m}^k \cdot \mathbf{B}^k + \frac{1}{2} K^k + K_0^k, \quad (2)$$

where the magnetic stiffness matrix \mathbf{K}^k and force vector \mathbf{B}^k are,

$$\mathbf{K}^k = \begin{bmatrix} K^k - 3\lambda_{100}T_1 & -3\lambda_{111}T_4 & -3\lambda_{111}T_6 \\ -3\lambda_{111}T_4 & K^k - 3\lambda_{100}T_2 & -3\lambda_{111}T_5 \\ -3\lambda_{111}T_6 & -3\lambda_{111}T_5 & K^k - 3\lambda_{100}T_3 \end{bmatrix}, \quad (3)$$

$$\mathbf{B}^k = [c_1^k K^k + \mu_0 M_s H_1 \quad c_2^k K^k + \mu_0 M_s H_2 \quad c_3^k K^k + \mu_0 M_s H_3]^T, \quad (4)$$

and λ_{100} and λ_{111} are magnetostriction constants. Magnetic domain orientations \mathbf{m}^k are calculated by minimizing each energy expression while constraining \mathbf{m}^k to have unity norm, resulting in,

$$\mathbf{m}^k = (\mathbf{K}^k)^{-1} \left[\mathbf{B}^k + \frac{1 - \mathbf{c}^k \cdot (\mathbf{K}^k)^{-1} \mathbf{B}^k}{\mathbf{c}^k \cdot (\mathbf{K}^k)^{-1} \mathbf{c}^k} \mathbf{c}^k \right]. \quad (5)$$

The anhysteretic volume fractions ξ_{an}^k of idealized magnetic domains oriented along each of the easy directions are then calculated by an energy-weighted average,

$$\xi_{an}^k = \frac{\exp(-G^k/\Omega)}{\sum_{k=1}^r \exp(-G^k/\Omega)}, \quad (6)$$

where Ω is an experimental averaging factor and r is the number of easy crystal directions, which depends upon crystal symmetry. Finally, bulk magnetization \mathbf{M} and magnetostriction \mathbf{S}_m are calculated as the sum of the contribution from each orientation (i.e., $M_s \mathbf{m}^k$) weighted by the volume fraction of domains in each orientation ξ_{an}^k ,

$$\mathbf{M} = M_s \sum_{k=1}^r \xi_{an}^k \mathbf{m}^k, \quad \mathbf{S}_m = \sum_{k=1}^r \xi_{an}^k \mathbf{S}_m^k. \quad (7)$$

The bulk strain \mathbf{S} is calculated as the sum of magnetostriction and mechanical strain. A benefit of this model is that it can be analytically differentiated to obtain partial derivatives of \mathbf{S} and \mathbf{M} with respect to \mathbf{T} and \mathbf{H} , thus providing an analytical expression for the effective elastic modulus of Galfenol $((\partial \mathbf{S} / \partial \mathbf{T})^{-1})$. The variation in Galfenol's elastic modulus as a function of stress and magnetic field calculated using the 1D formulation of the DEAM is shown in Figure 5. For semi-active applications, tuning of a magnetostrictive material's elastic modulus is performed using constant bias magnetic fields, one for each operating condition. Magnetic fields are thus held constant throughout the calculation of the composite's response.

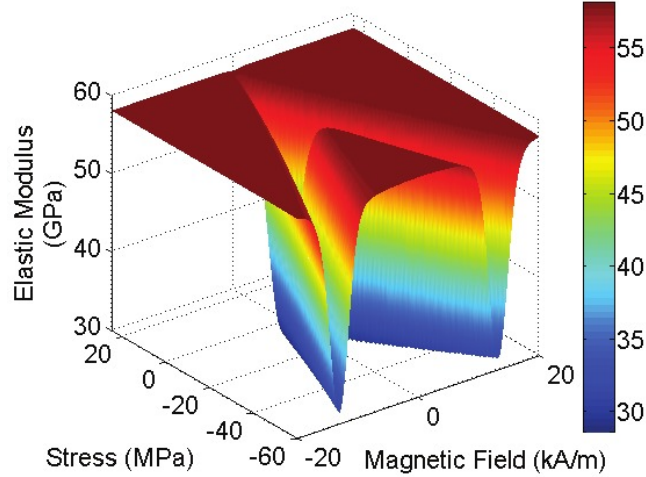


Figure 5. Galfenol's linear elastic modulus as a function of stress and magnetic field.

2.2 Single Degree of Freedom Composite Model

Following the standard application of Newton's 2nd law, the governing ODE for the system shown in Figure 4 is,

$$m\ddot{u} + c\dot{u} + K_{eq}(H_{bias}, T)u = m\omega^2 U_2 e^{i\omega t}, \quad (8)$$

where u is defined as the relative displacement between the mass and base, and harmonic base excitation with amplitude U_2 and frequency ω is used,

$$u = u_1 - u_2 = u_1 - U_2 e^{i\omega t}. \quad (9)$$

The damping ratio,

$$\zeta = \frac{c}{2m\omega_n} = \frac{c}{2m} \sqrt{\frac{m}{K_{eq}}}, \quad (10)$$

is held constant for all simulations. Using results from Meirovitch,⁸ the equivalent spring constant for a cantilevered beam is,

$$K_{eq}(H_{bias}, T) = \frac{3E_{eq}(H_{bias}, T)I(H_{bias}, T)}{L^3}, \quad (11)$$

where L is the length of the cantilevered beam. The equivalent elastic modulus of the composite E_{eq} is calculated as a function of the Galfenol and matrix elastic moduli (E_G and E_M) and volume fractions (ξ_G and ξ_M) using the rule of mixtures,⁹

$$E_{eq}(H_{bias}, T) = E_G(H_{bias}, T)\xi_G + E_M\xi_M. \quad (12)$$

The area moment of inertia I is calculated after first homogenizing the composite by scaling the Galfenol width to yield an equivalent section of matrix material,

$$W_{G_{eq}} = \frac{E_G(H_{bias}, T)}{E_M} W_G. \quad (13)$$

Following, the homogenized composite's cross-sectional geometry is split into n rectangular sections and the composite's area moment of inertia is calculated by summing the area moment of inertia of each section I_n about the composite's centroid, or neutral axis,

$$I = \sum_{j=1}^n I_n = \sum_{j=1}^n (\bar{I}_n + A_n \delta_n^2), \quad (14)$$

where A_n is the area of the n^{th} section, δ_n is the distance between the centroid of section n and the composite centroid, \bar{I}_n is the area moment of inertia of the n^{th} section about its centroid, and the parallel axis theorem has

been utilized. The area moment of inertia is therefore a function of the bias magnetic field and stress, because it is dependent upon Galfenol's elastic modulus. In this paper, an aluminum matrix is considered, because of the corrosion protection provided by the aluminum.

3. NONLINEAR SOLUTION PROCEDURE

The solution procedure is graphically depicted in Figure 6. The solution begins by defining all relevant system constants and simulation parameters, including the bias magnetic field, span of base excitation frequencies and amplitudes, and composite geometry parameters. Next, solution variables are initialized and the initial state is defined using the initial condition $T_0 = 0$. The excitation frequency and amplitude for the current frequency step are specified. Then the main incremental procedure is followed. This includes (1) updating the 1D composite stiffness using the material Jacobian calculated with the DEAM, (2) solving the linearized ODE over the current time step to determine the relative tip displacement at the end of the current step $u(t + \Delta t)$, (3) calculating the strain in the Galfenol element using the kinematic relationship $S = u/L$, and (4) calculating the stress in the Galfenol element using the inverse discrete energy-averaged model (IDEAM) with inputs of strain and magnetic field. This incremental procedure is repeated for each of the prescribed time steps. The nonlinear ODE governing the evolution of the relative displacement between mass and cantilever base is thus approximated. The time step is kept sufficiently small to yield a smooth and accurate time response.

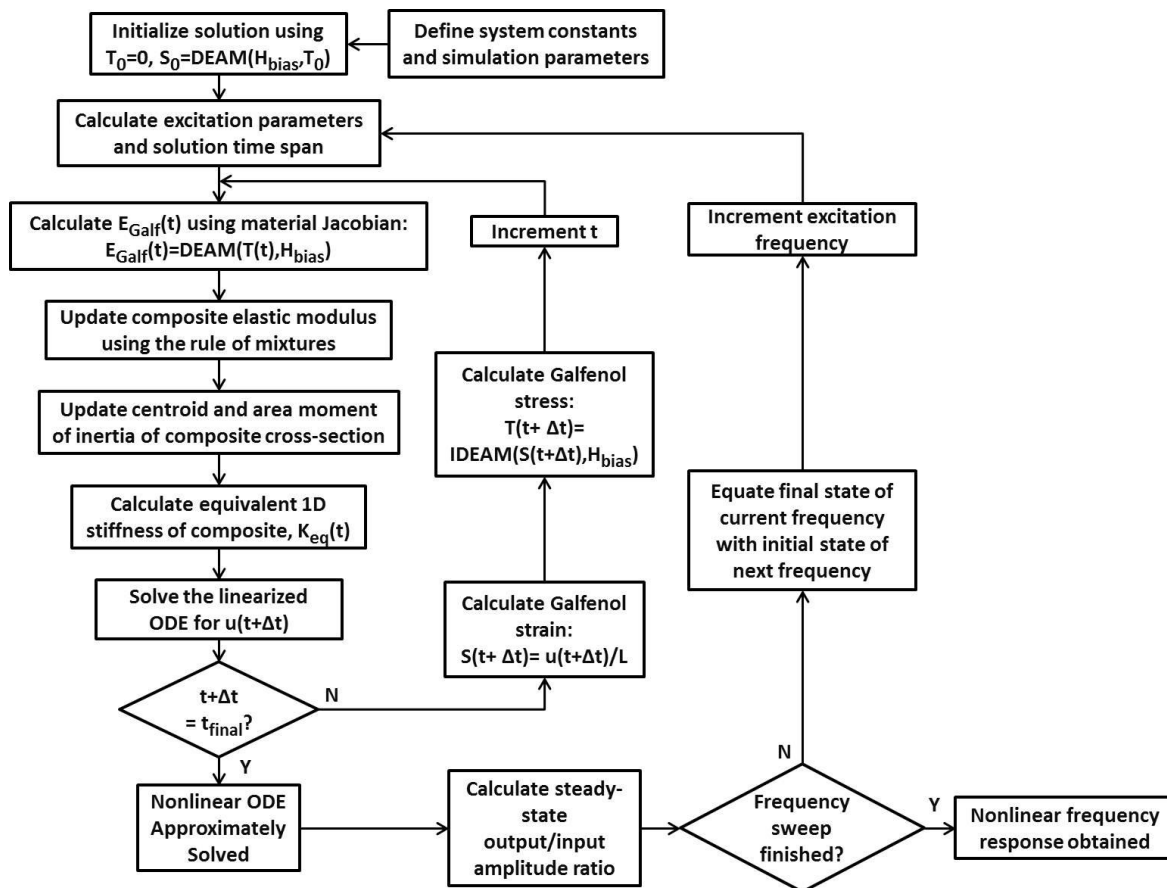


Figure 6. Solution procedure for obtaining the nonlinear frequency response of the composite's vibration.

From the nonlinear time domain response, the steady-state tip displacement is calculated as the average of the minimum and maximum tip displacement over the final 3 cycles of vibration. The amplitude ratio is then calculated as the steady-state tip displacement divided by the excitation amplitude. The next step is to determine if the desired frequency sweep has been completed. If yes, the simulation has completed and the

nonlinear frequency response has been obtained. If the frequency sweep has not been completed, then the initial state used to begin the nonlinear ODE solver for the next frequency step is equated with the final state of the response at the current frequency step, and then the frequency is incremented as the main incremental procedure is called again.

The response of nonlinear systems is often dependent on the initial conditions, because multiple stable fixed points or periodic trajectories may exist in the state space. When this occurs, it is seen in the frequency response as hysteresis in the steady state vibration of the system. The amount of hysteresis is a qualitative measure of the degree of nonlinearity in the system. To quantify hysteresis, forward and reverse sweeps of the excitation frequency are required. This also explains why the initial condition for each frequency step cannot be arbitrary, but must equal the final state at the previous frequency step. A hysteretic frequency response obtained using the proposed model is given in Figure 7.

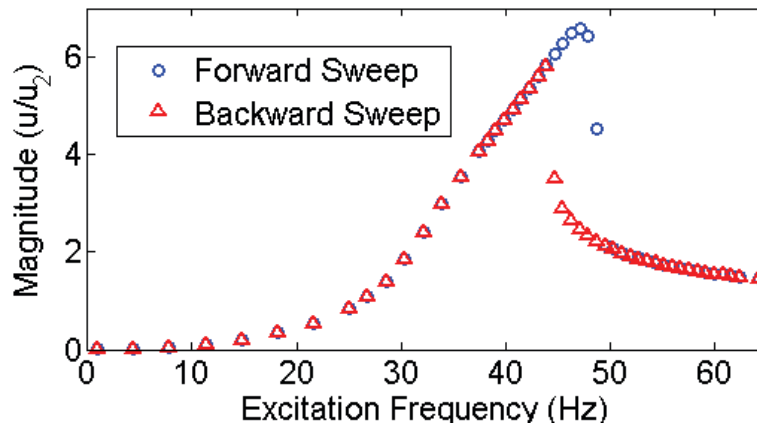


Figure 7. Hysteretic frequency response of the Al-FeGa composite, $H_{bias} = 3$ kA/m, $U_2 = 1.8 \times 10^{-6}$ m, and $\xi_G = 0.85$.

4. MODEL RESULTS

To fully characterize the stiffness tuning, and therefore natural frequency tuning, a range of excitation amplitudes and bias magnetic fields must be considered. This is due to Galfenol's elastic modulus, which varies with magnetic field and stress. The strain in the Galfenol element is directly related to the magnitude of the excitation amplitude for the single degree of freedom model. For a given strain and bias magnetic field, the stress in the Galfenol element is uniquely determined. Thus, the space of all possible excitation amplitudes and bias magnetic fields describes the entire range of behavior of the composite. A moderate range of excitation amplitude (1×10^{-7} to 4×10^{-6} m) and bias magnetic field (0 to 10 kA/m) was used. The 1D strain response of Galfenol is symmetric with respect to magnetic field. Therefore, negative bias magnetic fields do not need to be considered. To accurately approximate the natural frequency for each case, both the forward and reverse frequency sweeps were curve fit with cubic splines. The natural frequency was taken as the frequency at which the maximum amplitude ratio occurs in the interpolated data. In this way, the natural frequency of vibration for every combination of excitation amplitude and bias magnetic field was obtained. The resulting frequencies were normalized with respect to the max frequency to show the percent changes in resonance frequency from the saturated (stiff) case.

In order to determine the geometry that maximizes the stiffness tunability of the composite, the Galfenol volume fraction and the offset of the Galfenol element from the horizontal midplane of the composite's cross section were varied. Surface plots of normalized natural frequency were generated for each case. Model parameter values used in all simulations are given in Table 2; the material properties for Galfenol were obtained through a least squares optimization routine using the anhysteretic DEAM and experimental measurements of a highly-textured, polycrystalline $\text{Fe}_{81.6}\text{Ga}_{18.4}$ Galfenol rod.¹⁰

4.1 Effect of Galfenol Volume Fraction

For this analysis, the Galfenol element was located at the horizontal midplane of the composite's cross section, while the Galfenol volume fraction was varied between 25% and 100% (i.e., the limiting case of no surrounding

Table 2. Model parameters.

FeGa					Matrix (Al)	Composite				
M_s (T)	λ_{100}	λ_{111}	K^k (kJ/m ³)	Ω (J/m ³)	E (GPa)	ζ	L (m)	m (kg)	width (m)	thickness (m)
1.3787	1.57×10^{-4}	N/A	2.71×10^4	776.73	68.9	0.1	0.0254	0.058	0.01651	7.62×10^{-4}

matrix). The normalized natural frequency surface plot for each case is shown in Figure 8. The surface plots for negative bias magnetic fields are simply reflections about the $H_{bias} = 0$ line of those shown in Figure 8.

For a given excitation amplitude, semi-active control of the vibration absorber's resonance is accomplished by regulating the composite resonance between its minimum and maximum frequencies through changes in the bias magnetic field. At low excitation amplitudes, this can be achieved with magnetic fields between 0 and 5 kA/m. As the excitation amplitude increases, the magnetic field strength required to tune the composite's resonance also increases. This can be explained by referring to Figure 5. The Galfenol elastic modulus varies as the magnetic domains rotate between saturation states, where the magnetization and magnetostriction are saturated and essentially constant. When compressive stress is applied to the material, the energy of the magnetic domain orientations perpendicular to the stress decreases, while the orientations parallel to the stress increase in energy. The opposite is true for applied magnetic field and tensile stress. Thus, as compression is increased, stronger magnetic fields are required to rotate magnetic domains away from the perpendicular orientations; the rotation leads to magnetostriction and therefore a change in elastic modulus. Applied tension and magnetic field both act to orient magnetic domains along the direction of application, making the saturated state easily reached in the tensile regime. This explains the topography of Figure 5.

To reach a minimum average stiffness of the composite, the time that the Galfenol state spends in the elastic modulus trough (see Figure 5) must be increased. For harmonic excitations of a given amplitude, this time is maximized when the Galfenol state passes through the trough as the excitation reaches its maximum or minimum value. Thus, as the excitation amplitude, and therefore Galfenol strain range, increases, the bias magnetic field must also increase to keep the trough coincident with the minimum Galfenol strain. This explains the trajectory of the natural frequency troughs in Figure 8.

Even for a modest 25% Galfenol by volume, with Galfenol located on the neutral axis of the cantilever beam, limited control of the composite's natural frequency for *any* harmonic excitation is still possible by modulating the bias magnetic field. As the Galfenol volume fraction increases, the maximum potential reduction in composite resonance frequency from the saturated resonance increases from 6% to 50%. It can be seen in Figure 8 that this reduction increases nearly linearly as a function of Galfenol volume fraction. This can be explained by referring to the composite stiffness model given by (11) and (12). The rule of mixtures and equivalent spring constant are linear expressions, so the relationship between Galfenol volume fraction and composite stiffness is also linear. As such, the bandwidth over which semi-active vibration absorption is possible using the Al-FeGa composite increases linearly as the Galfenol volume fraction increases.

4.2 Effect of Galfenol Location

For this analysis, the Galfenol volume fraction was held constant at 25%, while the Galfenol location was varied vertically in the composite cross section. Four different cases were modeled: (1) the reference case—Galfenol midplane coincident with the composite midplane, (2) Galfenol midplane shifted upward 33% of the max value, (3) Galfenol midplane shifted upward 66% of the max value, and (4) the limiting case—top surface of Galfenol coincident with the top surface of the composite. The schematic in Figure 9 shows these cases, where the Galfenol element is offset horizontally only for visualization. Figure 10 shows the natural frequency surfaces for each case. These surfaces show similar topology to Figure 8 for the same reasons presented in Section 4.1.

The composite's area moment of inertia will vary regardless of Galfenol's location, due to Galfenol's Delta E effect. As the Galfenol element is moved away from the composite's horizontal midplane, the magnitude of the composite's area moment of inertia, and therefore stiffness, will decrease (Galfenol is more compliant than the aluminum matrix) while its variation due to changes in magnetic field or stress will increase. This is shown

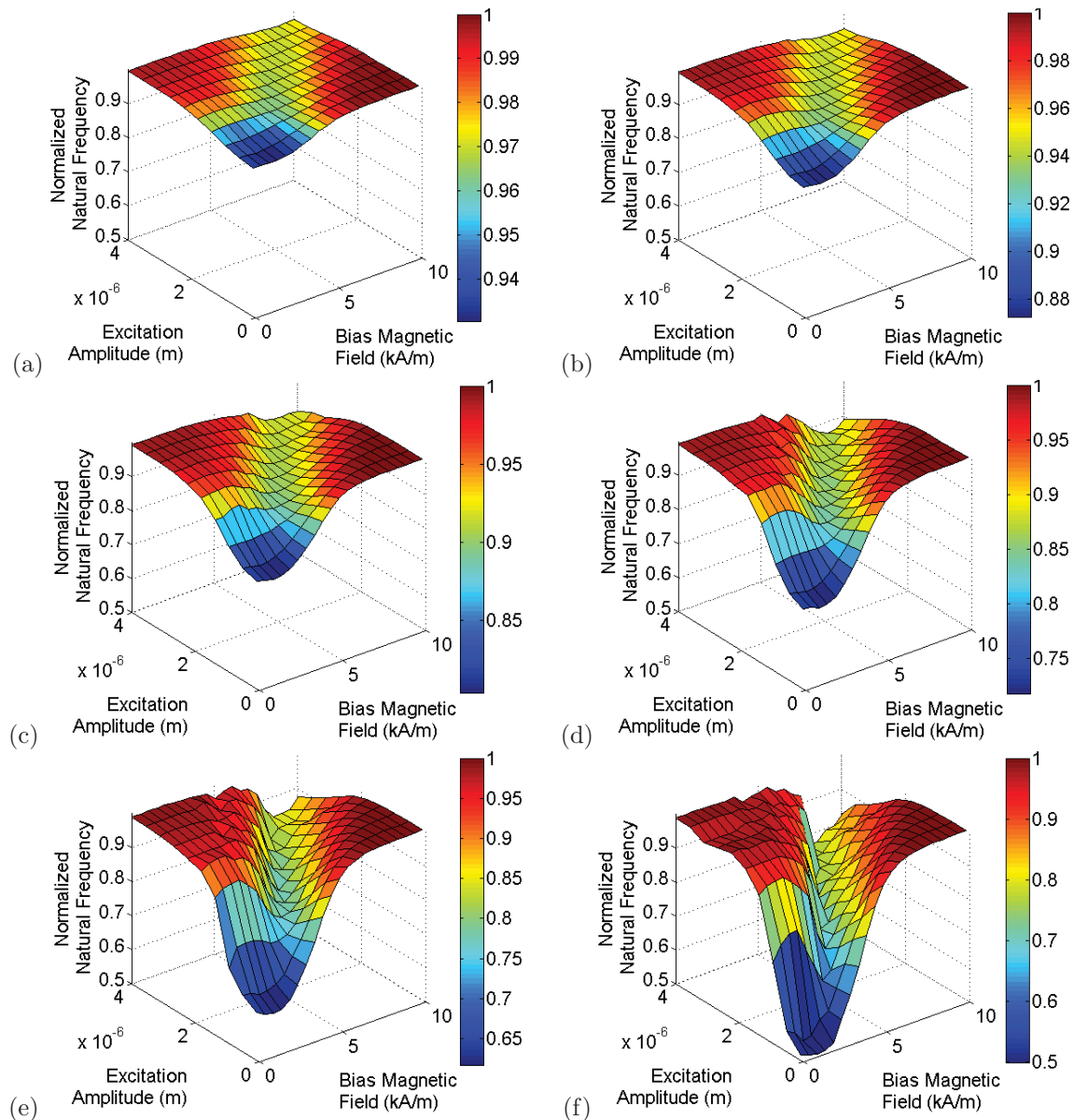


Figure 8. Normalized variation in natural frequency as a function of excitation amplitude and bias magnetic field for Galfenol volume fractions of (a) 25%, (b) 40%, (c) 55%, (d) 70%, (e) 85%, and (f) 100% (limiting case).

graphically in Figure 11. As seen in Figure 10, the range of natural frequencies over which the composite can be tuned increases quadratically with respect to the distance between Galfenol midplane and composite midplane. This is consistent with the parallel axis theorem of mechanics used to calculate the area moment of inertia of a section about an axis offset from its centroid. Therefore, the bandwidth over which semi-active vibration absorption is possible using the Al-FeGa composite increases quadratically as Galfenol is shifted away from the composite's midplane.

5. SUMMARY

In this research, resonance frequency tuning of a metal-matrix composite containing the magnetostrictive material Galfenol with an aluminum matrix was investigated. A single degree of freedom dynamic model of the cantilevered composite was developed using a fully nonlinear, anhysteretic Galfenol constitutive model from the literature.

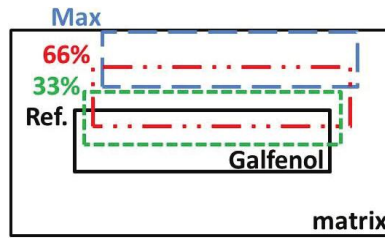


Figure 9. Galfenol locations within the composite cross section used for the optimization analysis (shifted horizontally for visualization purposes).

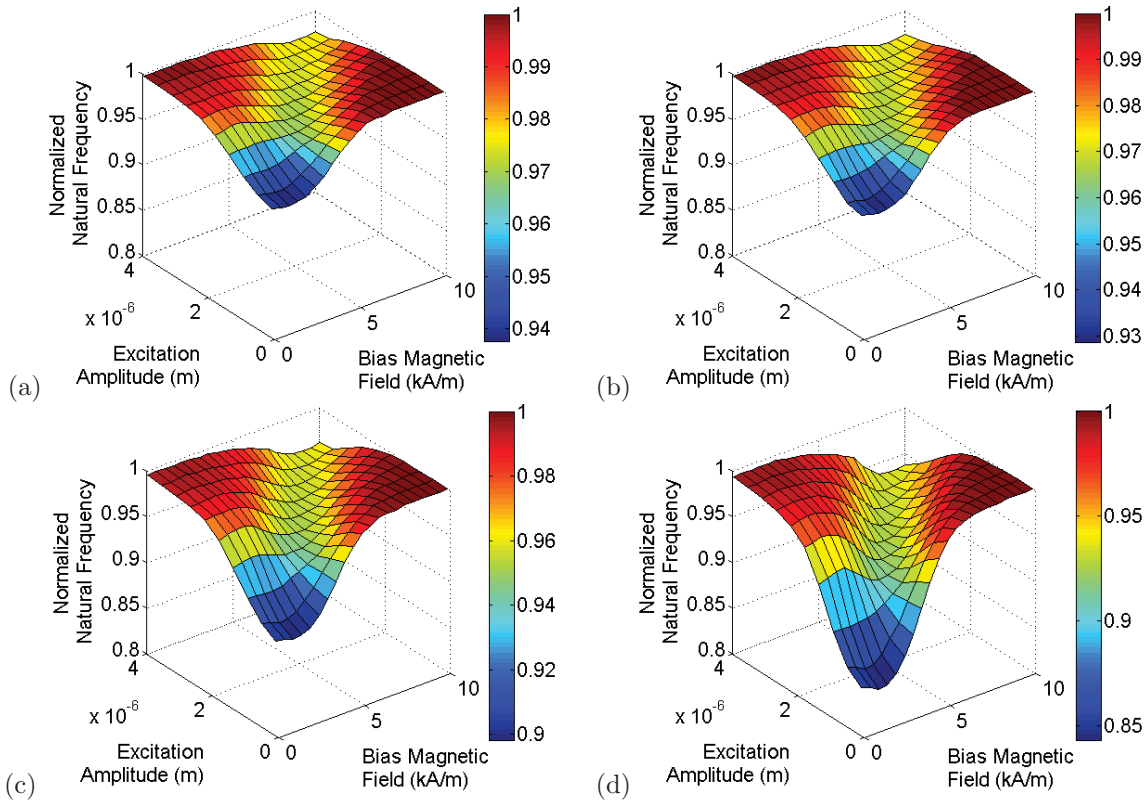


Figure 10. Normalized variation in natural frequency as a function of excitation amplitude and bias magnetic field for Galfenol locations (a) reference or min, (b) 33%, (c) 66%, and (d) 100% or max.

The nonlinear frequency response of the composite to harmonic base excitation was numerically obtained as a function of the amplitude of base excitation and the bias magnetic field in the composite. The maximum possible stiffness tuning effect occurred for excitation amplitudes below 1×10^{-6} m. For all excitation amplitudes above this threshold, the stiffness tuning effect was weakened, but remained essentially constant.

The relationship between the composite's natural frequency and the excitation amplitude and bias magnetic field was studied as the Galfenol volume fraction and Galfenol location within the composite were varied. A linear increase in the natural frequency tunability with respect to Galfenol volume fraction and a quadratic increase with respect to the offset distance between Galfenol and the composite midplane were found. Thus, for the maximum frequency bandwidth over which a Galfenol-based composite can be operated as a semi-active vibration absorber, the Galfenol volume fraction should be maximized and the Galfenol element should be located far from the composite's midplane.

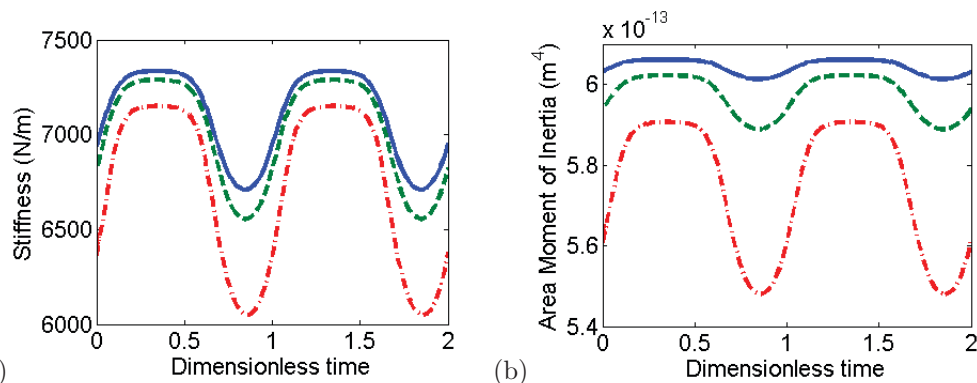


Figure 11. (a) Composite stiffness and (b) area moment of inertia variations for the reference (solid), 33% (dashed), and 66% (dash-dot) cases.

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